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14. ABSTRACT  Fuel sprays for aerospace propulsion systems tend to have high optical densities which causes difficulties in making quantitative measurements using conventional diagnostics. Using advance photon tools such as X-ray radiography can overcome some of these issues. These slides summarize some of the issuers related to rocket sprays and provides an overview of the X-ray methods that have been applied to date.					
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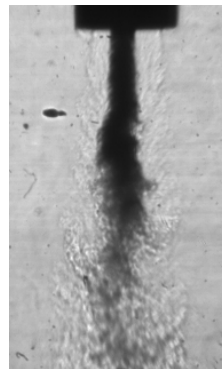


# Liquid Rocket Sprays

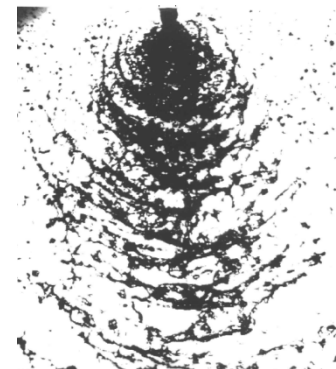
- **Quantitative spray data is lacking for liquid rocket injectors, especially in the near-injector region**
  - Quantitative data needed to develop scaling laws and validate models that reduce design time and cost
  - Near-injector region is of critical importance since this is typically where combustion occurs
- **Most liquid rocket injectors operate at conditions (high flow rates, velocities and pressures) which produce optically dense sprays that challenge or exceed the capability of most spray diagnostics**
  - Laser light is multiply scattered and insufficient useable light exits the spray to allow the use of laser diagnostics in the near-injector region
  - Liquid core, ligaments, and droplets can exist in the same area
  - Mist and density gradients are problematic during back pressure testing



**Gas Centered Swirl Coaxial**



**Shear Coaxial**



**Impinging Jet**



# Liquid Rocket Conditions

- Liquid rocket conditions that effect sprays vary greatly depending on engine class, engine cycle, injector type and propellant choice

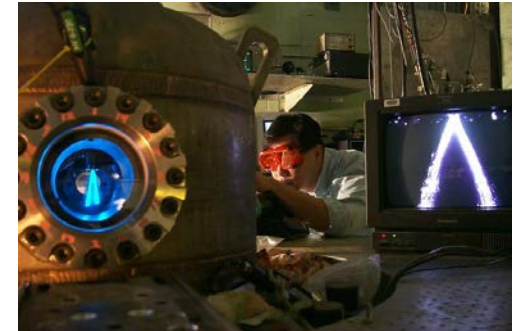
$$P_c \sim 10-200+ \text{ Bar}$$

$$\dot{m} \sim 5 \text{ g/s}-1.5\text{kg/s (Per Element)}$$

$$V \sim 1-200 \text{ m/s}$$

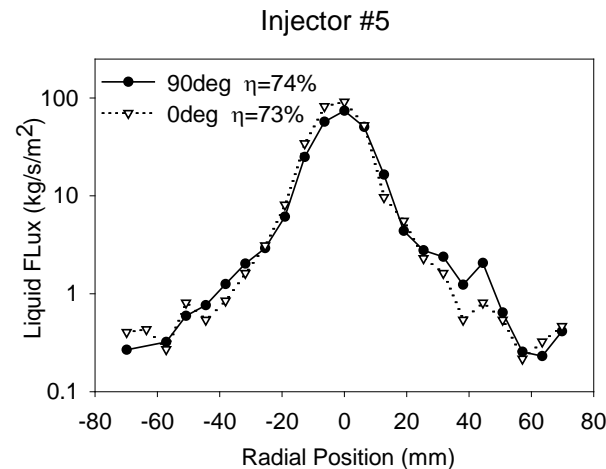


Duel GCSC Injector  
Atmospheric Testing



High Pressure Chamber (125  
Bar) with Optical Access

- Due to high spray densities mechanical pattenization is still in use in the rocket community
  - Only technique that can directly measure mass flux distribution
  - Intrusive: great care must be taken to not bias the results
  - Tends to a fairly coarse measurement

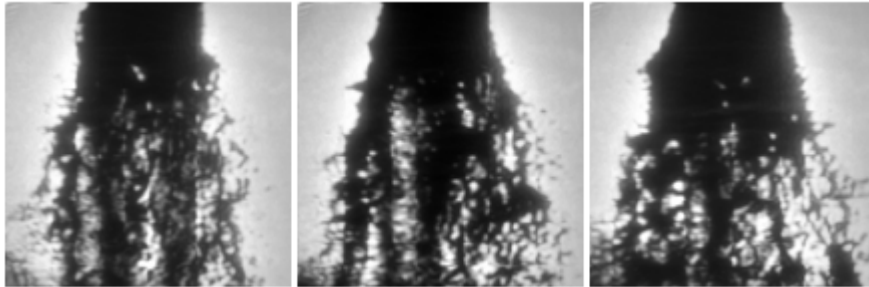




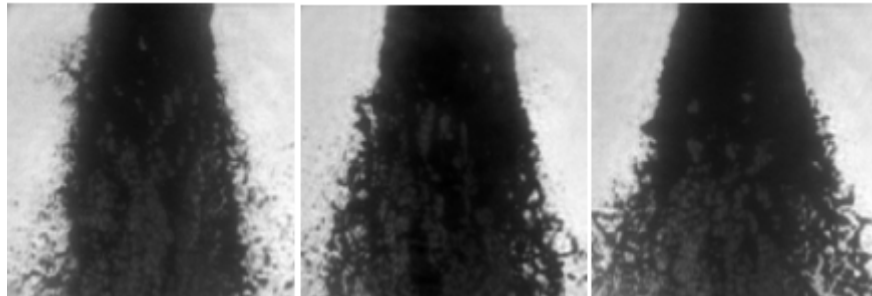
# Diagnostics

- **In the outer edges and downstream portions of sprays more conventional methods can be applied**
  - Laser sheet patternization, PDPA (droplet size & velocity), Laser diffraction (droplet size), shadowgraphy, etc..
  - When combusting these portions of the sprays are typically after the flame region
- **To penetrate the near field more advanced techniques such as Ballistic imaging or X-ray Radiography must be applied**

## Ballistic Imaging



Shadowgraphy



1.51 lpm

1.89 lpm

2.27 lpm

In this Gas Centered Swirl Coaxial Injector variant Ballistic Imaging was able to show ligament like structures persisting in the spray from the liquid inlet holes. Not observed in other imaging techniques or patternization.

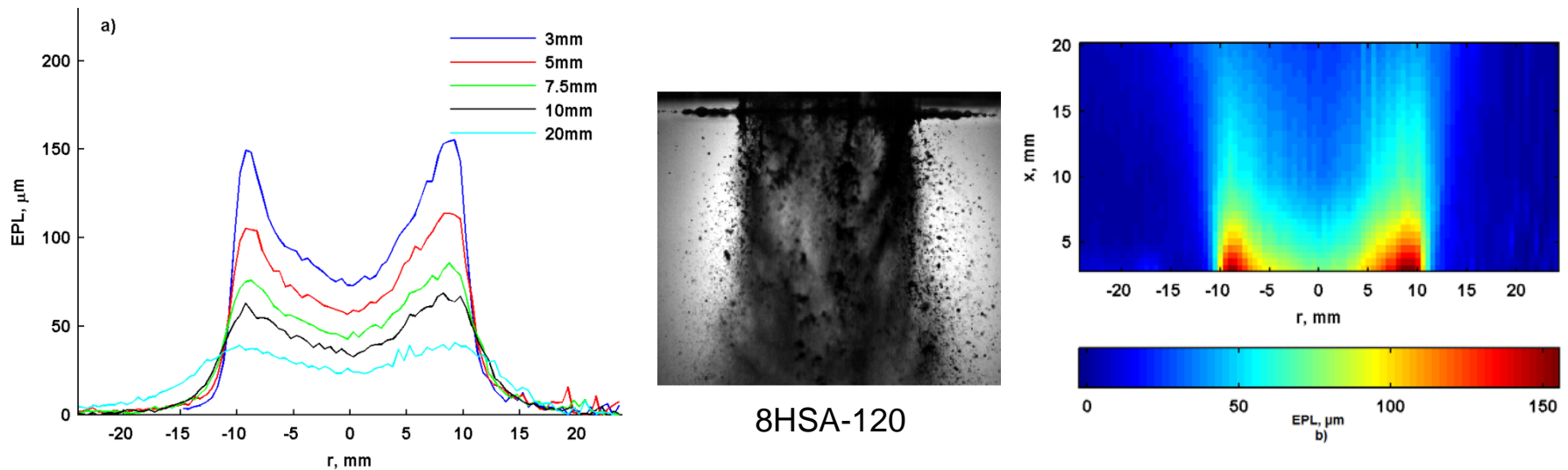


Type of Gas Centered Swirl Coaxial Injector (Air 227 lpm, H<sub>2</sub>O Listed Below)



# X-Ray Radiography

- **X-ray radiography is currently the only technique that allows quantitative results for mass distribution in the near-injector region for rocket sprays**
  - Measurements taken at 7BM using a custom high pressure flow system



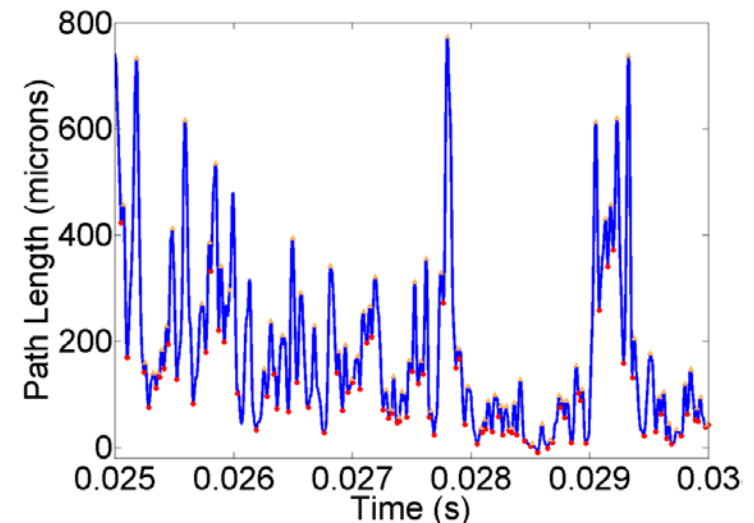
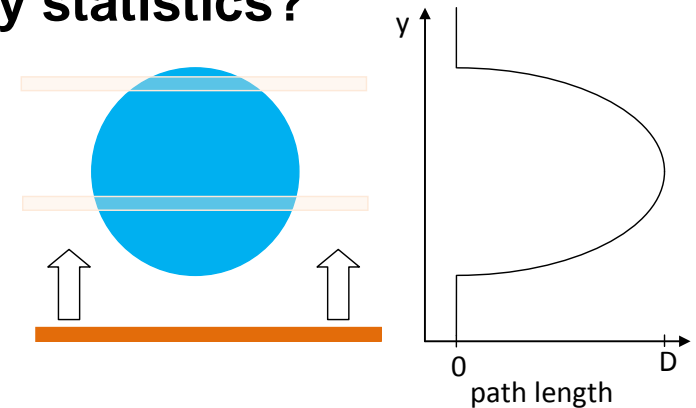
- Low EPL in spray center can be traced to large velocities ( $>120\text{m/s}$ ) in the spray center
- Measurements quantified a surprising level of asymmetry in the near-injector region



# Time Resolved: A Single Droplet



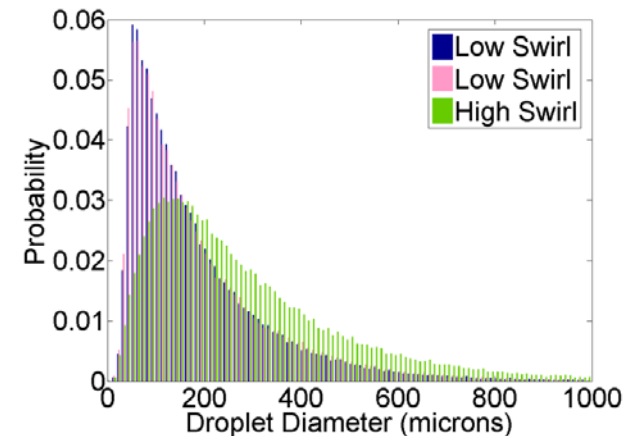
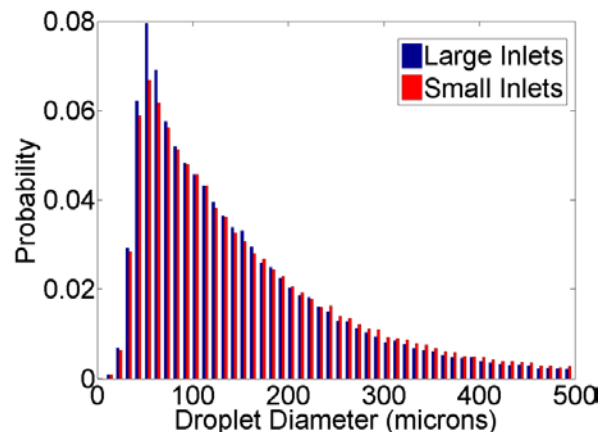
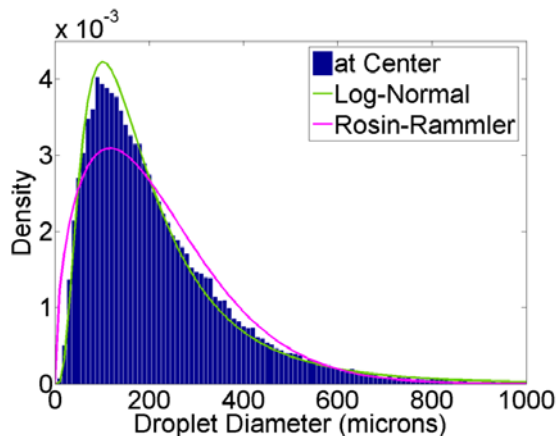
- **Can the x-ray radiography provide spray statistics?**
  - Prior radiography results have not extracted droplet information
- **Consider the simplest case of a single droplet moving thru the beam**
  - The peak of the path length corresponds to the droplet diameter
  - The elapsed time of departure from 0 path length relates to the velocity
- **A simple approach is taken to get droplet size and velocity from the data even where multiple droplets are in the beam**
  - Each peak in the data is a droplet
  - Its diameter is the offset from the bounding valleys (minimum)
  - Its velocity is related to the time between bounding valleys
  - This produces known biases, but demonstrates power of measurement





# Improving Injector Understanding

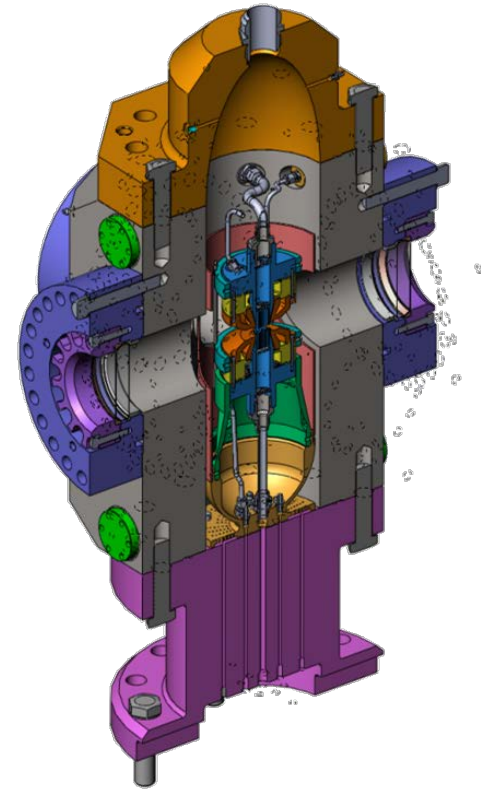
- **Even with multiple droplets in the beam, sizes and velocities can be extracted**
  - There are known biases in the technique and technique is not yet optimized
  - New methods are in the works and an improved data set has been collected
- **While these biases mean that the current assessments are only semi-quantitative, some useful results exist (for GCSC Injectors)**
  - Droplet distributions appear to be log-normal which is somewhat unexpected and likely a result of noise level in the data and biasing
  - Changing the liquid inlet size has little or no effect on the atomization and droplet-size distribution
  - However, changing the liquid inlet area (swirl) has a large effect on droplet-size distribution





# Outstanding Research Issues

- **While great progress has been made on rocket spray diagnostics work is still needed to push techniques to higher pressures and optical densities**
  - Current areas of Interest include:
    - A back pressure chamber (34 Bar) for X-ray measurements at APS
    - Laboratory X-ray radiography system for sprays that can't be tested at APS
    - Methods that can simultaneously measure gas and liquid phase
- **Efforts are needed to transition or develop techniques for combusting sprays**
  - Need to measure spray evolution and propellant vaporization at laboratory scale, but at realistic conditions (pressures, temperature, etc.)
  - Work is underway on high pressure combustion diagnostics, currently focused on the post flame region
    - fs-CARS, High-Bandwidth Time-Division-Multiplexed Lasers, MHz Burst Mode Laser



High pressure combustion (140 Bar) experiment currently under construction